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SUMMARY REPORT NO. 3.

ACCELERATION AND BLACKOUT

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Summary reports reviewing the more significant findings contained in reports from service and civilian laboratories in the United States and Allied Countries are issued from time to time. It is the purpose of these summaries to make available to flight surgeons and research personnel a brief survey of the information relating to a certain subject contained in the numerous and often voluminous reports in the files of the Air Surgeon. There is no assurance that the files are complete but it may be assumed that the summaries will fairly indicate the trend of work and opinions in the field. The information here reported is a review of the available reports and does not necessarily reflect the opinion of the Air Surgeon or his staff.

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ACCELERATION AND BLACKOUT

In operational flying, the human body and the plane are frequently subjected to forces many times greater than that due to the gravitational pull of the earth (1). Since the forces are proportional to and in the same direction as the accelerations, it has become a custom to use the observed acceleration as a measure of the magnitude and direction of the forces acting on the parts of the body. Accordingly, the degree of change in these forces is expressed as a multiple of one G, the acceleration due to the force of gravity. In operational flying, pilots may be subjected for a few seconds to more than 7 G (1). One survey indicated the time of maximum stress during various maneuvers varied from 3 to 10 seconds with an average time of about 5 seconds (45). Experience in flight and experiments in the laboratory both show that such forces acting for even these short periods may cause dangerous physiological effects in some individuals unless special precautions are taken. The danger arises primarily from the possibility of a temporary loss of vision or consciousness at critical times during combat.

Dimming of vision (Grey-out) is an early sign of dangerously high acceleration, (2, 45). If the acceleration is not increased further or not too prolonged, visual dimming may be the only effect. Otherwise this period of greyout is followed by blackout, or loss of vision (2, 45). At this time the subject is conscious but shortly may become unconscious (2). Under constant conditions, the greyout usually occurs at 1 G less than the blackout threshold and unconsciousness is produced by 1 G more than that producing blackout (45). When the duration and magnitude of acceleration is such that this sequence of events progresses only to blackout, there is a rapid uneventful recovery in a few seconds after cessation of acceleration (2). Recovery from unconsciousness, while a matter of seconds, may be accompanied by convulsions and may be followed by a period of disorientation (2). Thus, greyout or blackout should be regarded as important warnings to the pilot that he is close to his safe G-tolerance.

The G-tolerance of an individual depends principally upon the magnitude of the acceleration and its direction with respect to the long axis of the body, but, in addition, the time required to reach peak acceleration as well as the duration of this maximum stress are important (45).

Since a factor involved in determining the G-tolerance of a man is the direction of the forces with respect to the body axis, posture is important in minimizing the effects of high acceleration.

The physiological effects of acceleration are most marked when the forces act in the direction of the long axis of the body. Thus, about 5 to 6 G directed from the head to seat can cause unconsciousness in most men if continued a few seconds (1, 45). When the force is directed from seat to head in man, the field of vision becomes red, probably because of vascular congestion in the head regions. However, this "redding out" is not as common in operational flying as is blackout. On the other hand, much higher values directed transversely to the long axis have no important effect. In centrifuge experiments on animals, the forces most effective in disturbing visual function and brain waves were also those directed from the heart to the tail (5). Because of this importance of the direction of the force, the G-tolerance can be increased by assuming certain postures to be described later. (See pages 6-7.)

It is customary to employ blackout as the endpoint in estimating G-tolerance. In such tests the force is directed from head to seat. When the tests are done in a centrifuge, the time to reach maximum acceleration can be held constant. To further standardize the test, the magnitude of acceleration required to produce blackout in 5 seconds has been the criterion employed in Canada, (45).

Under these conditions the average threshold determined on 88 cadets was 4 to 6 G for most of the men. The total range of thresholds was 3.5 to 9 G, the individual thresholds being determined from at least 10 runs. These data indicate that the G-tolerance of a man may vary ± 1 G from day to day, but the variation on any one day is much less. The results are comparable to estimates based on flying experience where the test conditions are necessarily less well defined. Pilots in action, for instance, have reported tolerance of 3.5 G on one day to 5.5 G on the next (3). When special care was taken to keep the time of maximum acceleration constant, the blackout threshold on one individual in flight varied only 0.5 G (1).

Experience has shown that, within limits, the higher the acceleration the shorter the time to blackout. In tests or in flight, therefore, the shorter the time of exposure the higher the acceleration that can be tolerated without effects such as blackout (45). For example, the average cadet can tolerate about 6-G for two seconds and only about 4-G for ten seconds. In cats a similar relation between force and time holds when the reversible extinction of brain waves is taken as endpoint. Thus at 3-G or below, there is no extinction and above 8-G the time to extinction reaches minimum values of 8 to 12 seconds, depending upon the individual animal. This minimum time does not change with further increase in the force (5, 7). At 3 to 4 G the time to extinction of brain waves varies among individual animals

from 80 to 120 seconds (5). In general, as the force was increased the time to abolish the electrical activity of the brain was decreased. Though extinction of brain waves may be the more severe test when compared with loss of consciousness, it is reasonable to suppose that the same factors are involved in causing these two degrees of cortical depression. Thus the findings in animal experiments, using this endpoint, are of value in interpreting observations on man.

The most complete information on the "force-time" relations has been obtained on animals tested in a centrifuge, using killing rate as an endpoint. Over a range of 2 to 8 minutes and 6 to 25-G, the killing effect on rats is measured by a constant product of force and time, 50 G minutes (6). Since the endpoint used in these experiments was death of the animal, these results may have little bearing upon the study of the brief reversible effects of acceleration that are actually encountered in man.

Greyout and blackout are probably caused by loss of function in the retinal sensory cells. In the first place, a similar amaurosis is produced by a pressure of 300 millimeters of Hg. on the eyeball (7, 8), which visibly obstructs the retinal blood flow. It is thought that the resulting tissue anoxia raises the threshold for initiation of nerve impulses in the light sensitive retinal cells. It is also possible that this increased pressure has a direct effect upon the retinal cells. However, this seems unlikely because loss of response to a strong light is produced by that value of pressure that just stops retinal flow (7). A similar reduction of retinal blood flow is supposed to occur when the forces due to acceleration during flying impede the action of the heart in pumping blood to the head regions.

Since the degree of retinal ischemia and level of retinal anoxia can be graded, it is not surprising that there are graded changes in visual threshold up to complete blackout. Because of such gradations of threshold, the intensity of light is an important factor in testing for blackout or greyout (1). Thus, blackout in dim light may be only a greyout in bright light. As a consequence, the degree of acceleration tolerated by pilots before blackout depends upon the existing light intensity and is much less at dusk than in the day time. How much less is not known since the effects of acceleration on the sensitivity of the dark adapted eye have not been reported.

One explanation for the unconsciousness that occurs on exposure to high values of G for a few seconds is that the circulation to the brain is impeded or stopped just as is that to the retina. It

has been observed in cats and monkeys that under these conditions there is stasis in the pial arteries but no visible drainage of blood from the brain (7). In these animals the carotid blood pressure may fall to very low values in one second at 6 to 7 G.

It is thus possible that greyout and blackout precede unconsciousness in man because the intra-ocular pressure stops blood flow to the retina at a time when the systemic pressure still maintains some flow to the brain. Thus greyout or blackout should be regarded by the pilot as a useful warning of impeding unconsciousness if the existing acceleration is either continued or increased in magnitude. It is obvious that G-tolerance is a quantitative property and the magnitude of G acting parallel to his body axis should be known by the pilot at all times during training. For this purpose accelerometers should be in all training planes capable of achieving sufficient acceleration to produce deleterious physiological effects on the pilot.

A recent report from Canada (46) shows that in cats and monkeys subjected abruptly (in 1 to 2 seconds) to values of 7 to 10 G which are well above their threshold, the spontaneous cortical activity disappears first, then the cortical response to light disappears and finally the retinal cells and those of the optic pathway fail to respond. In such an experiment, the time course of events is similar to that following complete arrest of cerebral circulation by clamping the aorta. Under these conditions the delay in onset of failure of these several parts must be due to other than circulatory properties and is probably related to the relative oxygen requirements needed to maintain the various degrees of cellular action measured. In contrast, when the value of G is near threshold then the peripheral mechanisms fail first. As previously mentioned, this is probably due to the intraocular pressure stopping the blood flow to the retina at a systemic pressure that is still able to supply some blood to the brain. Thus, for threshold values of G, the peripheral vasomotor factors are important in determining time to blackout but when the acceleration is sufficient, essentially to stop blood flow to the head, then the susceptibility of the cells to anoxia seems to determine the time to loss of vision or consciousness.

The possibility that direct mechanical forces on the brain cells may play a part cannot be neglected. The intra-cranial pressure drops well below atmospheric pressure during positive G and rises above it during recovery (46). However, the effect of these forces is to prevent marked distortion of the brain and is thus probably beneficial.

The previously mentioned relation between force and time in producing a given effect in cats is presumably an expression of the relation between the degree of circulatory arrest and the rate at which the subsequent cellular anoxia develops. On this basis, one would expect that the minimum time for extinction of brain waves would occur when the acceleration was sufficient to arrest blood flow to the brain. In support of this idea, is the observation in animals that such a minimum time, 7 to 10 seconds, does exist (5, 7) for extinction of brain waves and is approximately equal to the extinction time following clamping of the aorta.

Perhaps a similar interpretation of the minimum times to produce unconsciousness or blackout by acceleration applies to man. In that event, the time to blackout and unconsciousness produced by occluding the carotid and vertebral arteries in man should be approximately equal to the minimum time for high acceleration to produce similar effects. The former measurements have been made on normal subjects (10). The time required to produce unconsciousness in the average subject was about 6 seconds. According to this hypothesis and these data, the minimum time to blackout during very high acceleration would be about 6 seconds in the average young man and would be produced by forces sufficient to arrest cerebral arterial flow. These predictions apply to the average healthy young man. One of the most interesting results revealed by this study (10) is the wide difference in individual susceptibility to the effects of cerebral ischemia. Thus the minimum time to unconsciousness was about 3 seconds and the maximum 12 to 14 seconds. Individual differences in human susceptibility to effects of acceleration have also been noted. This, however, is undoubtedly due to differences in vasomotor properties as well as to differences in resistance to the effects of cerebral anoxia. Which of these two factors is predominantly responsible for an individual's G-tolerance under operational conditions remains to be determined.

The fact that individuals differ in tolerance has lead to the suggestion that personnel be tested and classified according to their ability to withstand forces of acceleration (3, 11). To this end, the human centrifuge has been developed for research, indoctrination, and classification purposes.

In addition to the individual differences in the acceleration required to cause blackout, there are daily variations in the tolerance of the individual. It has been considered, however, that pilots differ sufficiently so that personnel with high G-tolerance can be selected by tests in a centrifuge (11). The data in report 45 on 88 cadets, show that classification is possible. About 2.5 percent of tested cadets can withstand 8 G for 5 seconds and 4.5 percent have a G threshold below 4 G. Most of the tested cadets, (21.5%) had a threshold at 5 G for 5 seconds.

In early tests the endpoint for G-tolerance was usually blackout though many subjects have become unconscious for a few seconds. (2). Recently, it has been shown (12, 13) that changes in peripheral circulation to the head can be employed as an index of the effect of acceleration. Thus, the blood content of the ear, measured by a photocell method, is reduced when a subject is accelerated in a centrifuge or in a plane (12, 13). The degree of change is related to the force acting from head to seat and the effect appears at lower values of G than are required to produce blackout. This procedure makes such tests much more acceptable to the subject, but it has not been extensively employed except for research purposes. In tilt-table tests, this objective sign appeared before greyout (44).

The most apparent disadvantage of the temporary blackout that may occur at high accelerations is that the pilot is handicapped for a few seconds during each such combat maneuver. Furthermore, there is evidence that repeated blackout may lower a man's G tolerance (45), thus making him more and more unfit for effective combat flying. There have also been reports of accumulative fatigue resulting from such stresses (1) and it is possible that this may contribute to the snydrome of chronic pilot fatigue. It is well to remember that acceleration, less than that required to blackout a man, may nevertheless cause temporary decrease of the cerebral oxygen supply. Such minor degrees of anoxia repeated a sufficient number of times may add up to an undesirable total duration of mild cerebral anoxia. This problem is closely related to the similar problem of accumulative effects of mild anoxia experienced for long times, at, for example, 12,000 feet with normal blood flow. The effects of moderate unsaturation of the blood undoubtedly aggravate the effects of temporary reduction in blood flow to the brain produced by acceleration. These relations are urgently in need of quantitative determination if we are effectively to prescribe the limits of reversible cellular strain resulting from unsaturation of the blood and decreased flow during acceleration at altitude. Tests made in a plane have demonstrated that anoxia does lower a subject's blackout threshold (40,42). At 10,000 feet the blackout threshold, 6.9 G when breathing oxygen, was lowered 0.5 G when breathing air. At 15,000 feet, breathing air, the blackout threshold dropped to 5.9 G in about one-half hour. This observer also reports no change in greying threshold up to 32,000 feet when breathing oxygen.

METHODS TO INCREASE G-TOLERANCE

It has been found that a crouching position increases G-tolerance by 1 to 2 G (14, 15, 16). This benefit can easily be obtained by raising the rudder bar so that the usual heart to ankle vertical distance is reduced by 6 inches or more (16). The protection afforded by the crouch position is probably obtained because of the prevention

of venous congestion in the abdominal veins which improves venous return of blood to the heart. Another factor is that the component of force acting from head to heart is reduced.

For this latter reason, the reclining position also affords some protection against effects of high acceleration. Reclining backward at 45° was sufficient to protect one subject against blackout at 5 G for 10 to 20 seconds. In the upright position, these same stresses uniformly produced blackout in this subject (17). It was estimated that the average fighter pilot could withstand action of 6 to 6.5 G in this position.

The most practical and effective method yet devised for protection against the forces developed during high acceleration seems to be the pressure suit. The principle is sound because it prevents the undesirable forces from acting upon the body by automatically producing opposite and equal forces during the acceleration. In effect the body is suspended in water so that the external hydrostatic force developed during acceleration everywhere compensates the action of the force within the body. In practice the water is contained in suitably placed pockets in a suit that is readily fitted to pilots. A rather surprising degree of protection is obtained from the 4 well-distributed pints of water (18, 19, 20, 21, 22, 23, 24, 25, 26). The suit has been considered favorably by pilots and greatly increases G-tolerance when tested in flight (21, 22, 25, 26). One subject whose blackout threshold in flight was 4.5 G for 10 seconds could withstand 6 G for 12 seconds when wearing the suit (26). One pilot reported "It is the opinion of the writer that the Franks suit in its present form (July, 1941) is a practical solution for the blacking out problem. It has been conclusively demonstrated that the wearing of the suit delays, if not eliminates blackout tendencies to beyond the practical limits of acceleration for which fighter aircraft are designed" (18). Such a sweeping endorsement of a "gadget" is seldom forthcoming after field testing.

In the suit developed by Dr. Cotton of Sydney University, the forces produced in the body by acceleration are opposed by an air pressure gradient distributed over the body by means of proper valves (27, 28, 29, 30, 31, 32). The device must be connected to an air compressor and thus ties the wearer to the plane. The advantage of the method over the water-suit is that the air pressure need only be turned on when the acceleration is anticipated. Wearing this suit, Dr. Cotton was able to withstand the effects of 11 G for 18 seconds in a centrifuge (27). Recent tests of pneumatic suits during mock combat have shown them to be practical and effective in increasing G-tolerance.

Tests have been made to determine whether or not abdominal pressure belts would significantly increase G-tolerance by preventing pooling of blood in the abdominal veins (33). A prolonged constant pressure was found to lower blackout threshold while inflation of the belt just preceding the acceleration gave some protection (33). The belt is considered a dangerous device because even if adjusted right, long duration of G can cause it to block venous return. The method was considered cumbersome and not fool-proof. Tests in the air of Spencer acceleration belts and leggings showed an increase of 1 G in the blackout threshold of the wearer. The devices were inflated 10 to 30 seconds before the acceleration (34). Other tests of similar apparatus led to the conclusion that 1.5 pounds pressure in leggings and belt protected against persistent blackout as long as the acceleration was less than 5.5. G (35). In these tests an initial blackout at 5 G always occurred for 1 to 4 seconds regardless of the pressures employed, but the vision then cleared for 12 to 34 seconds. Early tests indicated that abdominal belts alone are of no use (36).

A thorough study of the effect of abdominal belts on the flow and distribution of blood has been made (37). The calf volume increased when the pressure in the abdominal belt was 100 mm Hg. Venous return of blood to the heart was impeded to a degree that was greater when the subject was vertical then when supine. The total blood flow remained essentially constant but more blood circulated below the heart than above it when the subject was erect and wearing the belt. The relation of these basic observations to the use of pressure belts and leggings is discussed.

In another series of tests (43), benzedrine, glucose, adrenalin, and eschatin were found to have no effect on the blackout threshold. The possible action of desoxycorticosterone has been discussed (41).

There is one aspect of the acceleration problem that has received too little attention: The investigation of the effects of degrees of cerebral anemia insufficient to cause blackout or other immediate symptoms. Such moderate cerebral anemia must be present even at 2 or 3 G. Though not subjectively annoying, it may be a cause of pilot fatigue. In principle, the graded action on man of all tolerable ranges of G should be examined experimentally. If moderate values of acceleration, insufficient to produce blackout or unconsciousness, have important physiological effects on pilots then protective devices may be even more widely useful than is now apparent. The partial-protection devices such as inflatable belts and leggings may here find their correct application. Such applications of G-suits are to be regarded as protective in nature, but a G-suit or other means devised to enable

men to increase their top limits of G-tolerance is to be regarded as a method to gain tactical advantage at the expense of some physiological strain associated with marked cerebral anemia.

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